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Characteristics of Pozzolan and Composite Portland Cements for Sustainable Concrete's Material

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Abstract – To support sustainable materials, the ordinary Portland cement production has been reduced since it left a high carbon footprint during manufacturing. As an alternative, the use of pozzolan Portland cement and composite Portland cement has been encouraged because they are more environmentally friendly. This paper examines some characteristics of cement made from pozzolan Portland cement (P.P.C.) and composite Portland cement (P.C.C.). The testing procedures were carried out on chemical and physical testing on P.P.C. and P.C.C. In addition, the mechanical testing of concrete made from both types of Portland cement and their combinations were conducted under compression load. Furthermore, the surface hardness of the concrete was evaluated using a rebound hammer measurement. Concrete testing was conducted after the curing age of 7, 28, and 42 days. According to chemical examination, P.P.C. has higher silica (SiO_2) and iron (Fe_2O_3) than those of P.C.C., whereas P.C.C. has a higher lime (CaO) content. Compared to P.P.C., P.C.C. shows faster initial and final setting time. This result is proportionally influencing the strength development of concrete. P.C.C. concrete offers significant strength development at an earlier age. Meanwhile, P.P.C. concrete reacts slower at an earlier age, but it improves the compressive strength at a later age. The mix combination of 50% P.P.C. and 50% P.C.C. in concrete shows the highest average compressive strength and surface hardness. This combination achieves the average compressive strength of 30.27 MPa, 35.27 MPa, and 35.93 MPa respectively for 7, 28, and 42 days curing time. Furthermore, this concrete also shows the most remarkable characteristics of Young's modulus and surface hardness.

Keywords: sustainability concrete, pozzolan Portland cement, composite Portland cement

Introduction

Concrete can be considered as a sustainable material in construction. It has been used since in the past until now. Sustainability material, especially for building material, is such materials that enable to improve the quality of life and working conditions and reduce their negative impacts on the environment. Therefore, in terms of concrete, sustainability concrete means that it not only stays for such a long-time application but also possess the properties to meet the requirement for sustainability materials as being demanded above.

Sustainability concrete is categorized as the concrete which enables to minimize energy and carbon dioxide (CO_2) during production, minimize water use, increase the use of recycled content, increase the use of environmental waste, minimize the process needs, minimize cost and society benefits. Portland cement is one of the crucial components in concrete production. Ordinary Portland Cement (O.P.C.) is the most widely and commonly used cement in the world. This type of cement is manufactured to be powder by mixing natural resources such as limestone and other raw materials, which consist of argillaceous, calcareous, and gypsum. During cement manufacturing, it produces CO_2 emission, which is divided into process emission by more than 50%, thermal emission by 40%, and others such as grinding and transporting by 10% (Jin et al., 2015; Rodgers, 2018; Singh and Subramaniam, 2019). For the shake of sustainable material issues, the use of alternative cement has been encouraged nowadays. The studies on the addition or replacement materials in cement to promote

sustainability concrete have been published (Parande et al., 2011; Al-Chaar, 2013; Assi et al., 2018; Adesina and Olutoge, 2019; Mindess, 2019; Singh and Subramaniam, 2019). For instance, the use of natural pozzolan, which was rice-husk ash and lime or RHA-Lime, has been reported by Adesina and Olutoge (2019). It is found that RHA-Lime concrete achieves higher early strength than that of control concrete. Furthermore, considering the strength, RHA-Lime cement mixes are appropriate in the structural application and can replace conventional cement up to 25%. Therefore, it is encouraging to be a substitute material for conventional cement in concrete.

Currently in Indonesia, Pozzolan Portland Cement (P.P.C.) and Portland Cement Composite (P.C.C.) are the types of alternative Portland Cement, which are commonly found commercially. Ordinary Portland Cement (O.P.C.) has rarely been found commercially. P.P.C. and P.C.C. employ natural and industrial waste, which reduces environmental pollution and lower cost and emission during manufacturing. P.P.C. is a hydraulic cement consisting of a homogeneous mixture of Portland cement with fine pozzolan, which is produced by grinding Portland cement clinker and pozzolan together or mixing evenly of Portland cement powder with pozzolan powder, or a combination of grinding and mixing, where the levels pozzolan 6 to 40% mass of Portland pozzolan cement. Meanwhile, P.C.C. is a mixed hydraulic binder together with slag Portland cement. It casts with one or more inorganic materials, or the result of mixing Portland cement powder with other inorganic powder. The inorganic materials include high blast furnace (blast furnace slag), pozzolan, silicate compounds, limestone, with a total content of inorganic material 6% - 35% of the mass of Portland composite cement (S.N.I. 0302:2014, 2014; S.N.I. 7064:2014, 2014).

However, people are still reluctant and questioning the quality of P.P.C. and P.C.C. It is assumed that concrete made from P.P.C. and P.C.C. have lower strength than concrete made from O.P.C. As reported by Al-Chaar (2013), concrete with the addition of pozzolan as cement replacement shows varying mechanical properties depending on the proportion of pozzolan added during the mixing process. The strength of concrete with the addition of pozzolan has been seen significant at more than 28 days of concrete age. But at an earlier age, the mechanical strength is smaller than that of concrete with O.P.C. Furthermore, it is observed by Parande et al. (2011) that P.P.C. concrete exposed to severe environments such as sewage water and industrial wastewater shows better performance than O.P.C. concrete in both mechanical and electrochemical studies. The use of alternative cement is still debatable; therefore, this research is trying to study the properties of the P.P.C. and P.C.C. and the concrete made from both cement in terms of chemical composition, physical and mechanical properties experimentally.

Materials and Methods

Materials

P.C.C. and P.P.C. were the primary materials utilized in this research. These types of cement were commonly available in the market in 50 kg packaging. The variation of both types of cement used in concrete is presented in the sub-section of the concrete mixture proportion.

Crushed aggregate was used as coarse aggregate; meanwhile, the fine aggregate was the natural type aggregate. The maximum size of the coarse aggregate was 20 mm. The specific gravity of coarse and fine aggregate was 2.59 and 2.62, respectively. Besides, the water absorption of the coarse aggregate was 1.68%, whereas the water absorption of fine aggregate was 2.62%. The aggregate meets the requirement of the Indonesian standard of aggregate for making concrete (S.N.I. 03-1750-1990, 1990).

Concrete mixture proportion

For investigating the properties of both P.P.C. and P.C.C.'s concrete, four mixture proportions were prepared, as shown in Table 1. The first and second proportions were entirely made from the cement type of P.P.C. and P.C.C., respectively. Then P.P.C. and P.C.C. were blended into two variations. The first was P.P.C. 50% and P.C.C. 50%, and the second was P.P.C. 75% and P.C.C. 25%.

The variation of cement content in the mixture proportion was considered based on the chemical examination, where P.P.C. contained more silica than P.C.C.; therefore, a more significant proportion of P.P.C. was assumed to reach better concrete mechanical properties. The water-cement ratio was kept by 0.45, and the mixture proportion of each component was kept the same except the cement content.

Table 1. Concrete mixture proportion

Cement Proportion	Water (kg)	Cement (kg)		Gravel (kg)	Sand (kg)
		PPC	PCC		
PPC 100%	246	451	–	934	771
PCC 100%	246	–	451	934	771
PPC (50%) : PCC (50%)	246	226	226	934	771
PPC (75%) : PCC (25%)	246	338	113	934	771

Method of testing

The specimen was concrete cylinders with a diameter size of 150 mm and a height of 300 mm. The testing was conducted on cement powder, cement paste, and concrete cylinder. Chemical testing was applied to cement powder to evaluate the composition of silica, calcium, and iron in P.P.C. and P.C.C. The chemical composition of each cement was further considered as the proportion of blended cement, as shown in Table 2. The physical examination was conducted on cement paste to evaluate the initial and final setting time of P.P.C. and P.C.C. The testing was based on the Vicat Test procedure (S.N.I. 03-6827-2002, 2002).

The mechanical testing was applied to the concrete cylinder. Before concrete casting, the fresh concrete properties were evaluated using a slump test. The hardened concrete was subjected to compression loading until failure after the curing age of 7, 28, and 42 days. Additionally, during compression testing, the concrete deformation was recorded to obtain the stress-strain curve and to analyze the Young's Modulus. Another physical testing to the concrete specimen was delivered using non-destructive apparatus, which was rebound hammer testing to determine the surface hardness (SNI ASTM C805-2012, 2012). The entire testing methods are summarized in Table 2.

Table 2. Method of testing

Method of test	Measurement	Test result
Chemical testing	Chemical composition	Silica content
		Lime content
		Iron content
Physical Testing	Setting Time	Initial setting time
		Final setting time
	Workability	Slump value
Mechanical Testing	Compression loading and deformation	Compressive strength
		Young's modulus
		Stress-strain curve
Non-Destructive Testing	Rebound hammer	Surface hardness

Results

Chemical composition

Table 3 shows the chemical composition of the P.P.C. and P.C.C. P.P.C. contains greater silica and iron than P.C.C.; meanwhile, P.C.C. contains more significant lime than P.P.C. If silica and calcium react, they form tri-calcium silicates (C_3S) and di-calcium silicates (C_2S) compounds, which provide strength and binding effect to the aggregate. The compounds have the composition that makes up 70-80% of cement. Of equal importance, P.C.C. contributes to long term strength gaining due to higher lime content (Singh and Subramaniam, 2019).

Table 3. Chemical Composition

Composition (%)	Cement Type	
	PPC	P.C.C.
Silica (SiO_2)	24.17	18.71
Lime (CaO)	66.7	72.45
Iron (Fe_2O_3)	3.21	2.14

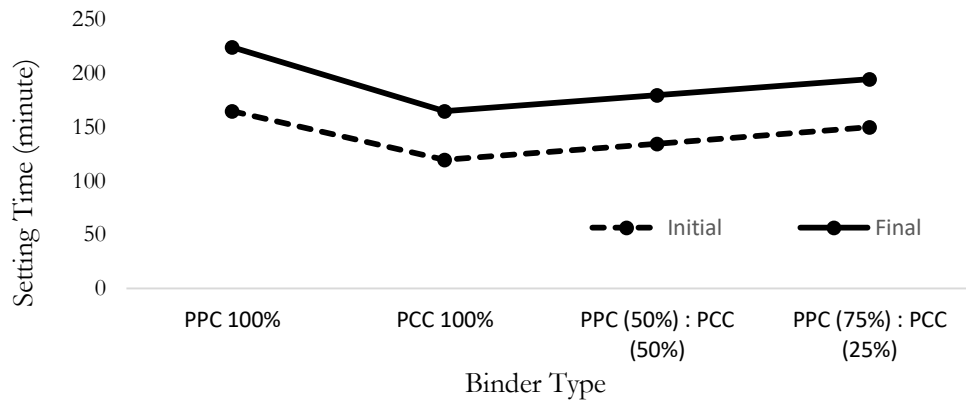


Figure 1.

Setting time

Figure 1 gives the initial setting time and final setting time of P.P.C. and P.C.C. P.C.C. has the fastest setting time both in terms of initial setting time and last setting time. On the other hand, P.P.C. has the longest setting time. P.P.C. setting time has a value of about 1.3 times the P.C.C. setting time value. After both cement types are mixed equally, the results of the setting time show the values between the original values. P.C.C. reacts faster than P.P.C. due to higher lime content in P.C.C. This is in line with the findings of (Nawaz et al., 2016; Jaafri et al., 2019), showing that higher lime content leads to faster setting time.

A considerable amount of initial setting time is needed to provide concrete practitioners with the opportunity to work during the concrete manufacturing process. Short setting time can enable concrete hardening faster. Therefore, construction work can be finished more quickly because it is easy to dry. However, such this condition is not solely as the requirement in construction since it tends to induce more shrinkage microcracks in concrete (Tjokrodinuljo, 2007). The final setting time indicates the chemical reaction of the cement with

Fresh concrete slump

Table 4 shows the fresh concrete slump. The slump value indicates the workability of the concrete. All mixtures show proper workability since the slump value adequate for a requirement of concrete work practical standard. However, P.C.C. concrete has the lowest slump, and the highest is shown by P.P.C. concrete. P.C.C. consists of more lime in which need more water to be workable. Therefore, the slump of P.C.C. concrete decreases since the water-cement ratio was kept the same among the mixtures. The slump value for concrete with the blended P.P.C. and P.C.C. is between the slump value of P.P.C. and P.C.C. The greater proportion of P.C.C. in concrete shows a lower value of slump.

Table 4. Fresh concrete slump

Specimen	Slump (mm)
PPC 100%	95
PCC 100%	88
PPC (50%) : PCC (50%)	90
PPC (75%) : PCC (25%)	92

Compressive strength

The compressive strength of the concrete is presented in Figure 2. In general, P.P.C. concrete has a higher compressive strength than P.C.C. concrete. P.P.C. concrete shows a normal strength development from 7 days until 42 testing days as required by code where the ratio of the strength of 7 days is around 0.8 times to the strength of 28 days and the ratio of the strength of 42 days is around 1.1 times of the 28 days strength (S.N.I. 03-2834-2000, 2000). On seven days of curing time, the compressive strength of P.C.C. concrete is higher than that of P.P.C. concrete. Due to faster setting time, then on 28 days, the compressive strength grows significantly, which is almost the same as 42 days compressive strength. Otherwise, P.P.C. concrete reacts slower at an earlier age, but it improves the compressive strength at a later age.

The slower strength development of P.C.C. concrete at an earlier age than that of the commercially available Portland cement concrete has been reported by (Singh and Subramaniam, 2019). Similarly, it is also confirmed that P.C.C. concrete achieved a lower compressive strength. Although P.P.C. has excellent characteristics on preliminary test results, in the form of concrete, concrete with a mixture of 50% P.P.C. and 50% P.C.C. shows the highest value on each curing day. Likewise, concrete with the ratio of P.P.C. 75% and 25% P.C.C. even though prior to the testing age of 28 days shows a lower compressive strength, but after 28 days shows a significant compressive strength development which is similar to concrete with a ratio of 50% P.P.C. and 50% P.C.C. After 42 days of curing time, concrete with an identical proportion of P.P.C. and P.C.C. reaches the highest compressive strength among the mixture proportion. This combination achieves the average compressive strength of 30.27 MPa, 35.27 MPa, and 35.93 MPa respectively for 7, 28, and 42 days of curing time. It is assumed that the continued pozzolanic reaction occurs properly and contributes strength in the later stage.

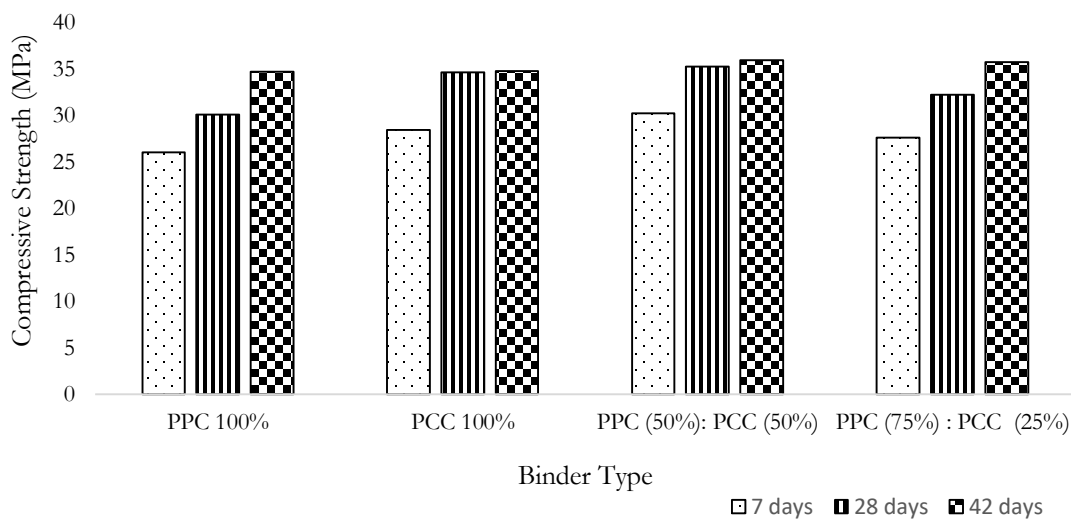


Figure 2. Concrete compressive strength

Young's modulus

Young's modulus is obtained based-on the secant modulus of elasticity procedure. The value of Young's modulus corresponds to the compressive strength. Young's modulus increases with increasing concrete age. Concrete with binder mixture of 50% P.P.C. and 50% P.C.C. produces the concrete with the highest Young's modulus value. However, in general, the value of Young's modulus for all concrete types is still in the range of static modulus of elasticity for regular concrete, which is around 20000-30000 MPa. Figure 3 presents Young's modulus obtained for 7, 28, and 42 days in each binder type.

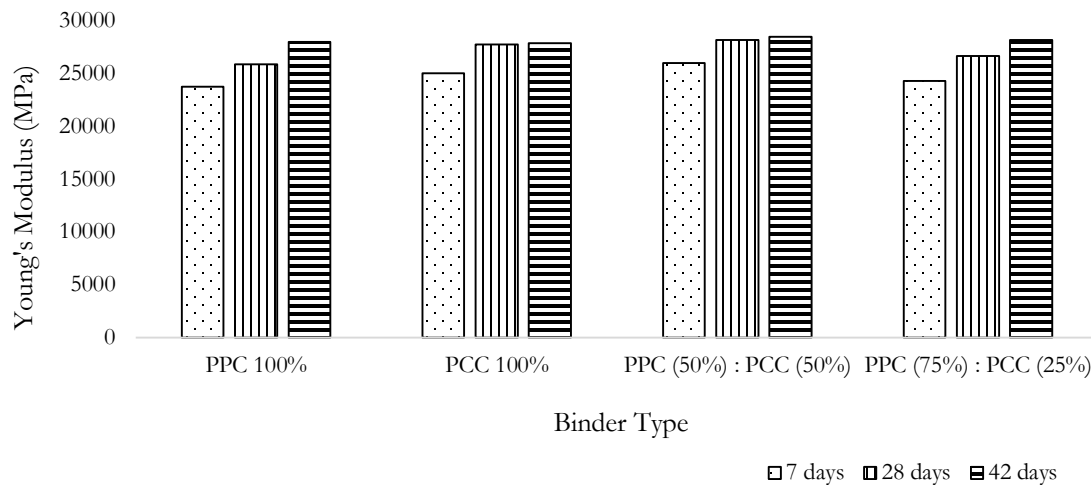


Figure 3. Concrete Young's modulus

Stress-strain curve

In general, all types of concrete show a similar shape where the curve initiates from the proportional line between stress and strain. Then it turns into a plastic condition before the ultimate failure when the strain approaches 0.0025-0.003. The proportional limit stress in all types of concrete is almost similar to about 30% of the maximum stress. Beyond this limit, the microcracks appear, and as the increase in axial load, the larger cracks are formed gradually until the peak stress reached.

Furthermore, on the later stage of curing time, concrete behaves more ductile because there seems to be an extension of the curve after the maximum stress. Ductile material is preferable in construction to prevent sudden failure. The graph of the stress-strain relationship is illustrated in Figures 4-6 for each curing age.

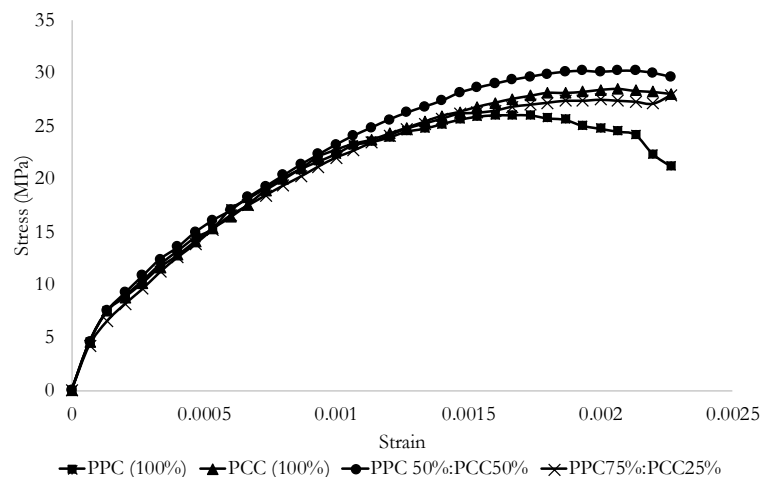


Figure 4. Stress-strain curve under compression load at seven days of curing age

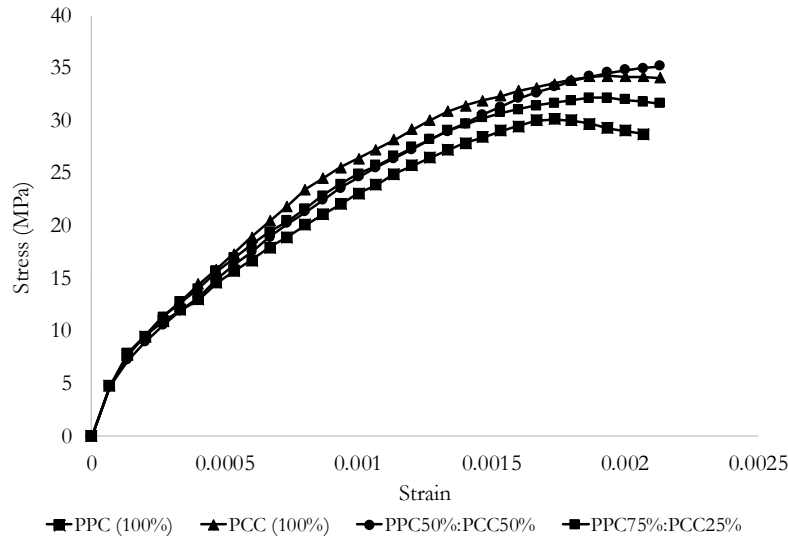


Figure 5. Stress-strain curve under compression load at 28 days of curing age

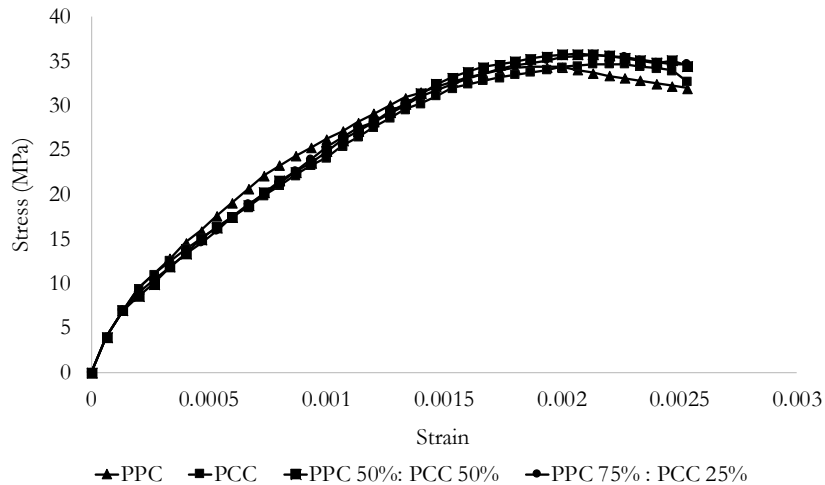


Figure 6. Stress-strain curve under compression load at 42 days of curing age

Surface hardness

The surface hardness of concrete was measured with a rebound hammer test. Several factors influence the rebound number; one of the factors is the type of cement (Szilágyi et al., 2015). Hammer rebound number is generally associated with concrete compressive strength. However, in this paper, the rebound numbers are utilized to evaluate the surface hardness of each type of concrete made by different types of binders to evaluate the effect of cement type of concrete surface hardness. Table 5 shows the rebound number of concretes made of P.P.C. and P.C.C. and the blended between them.

In general, on each curing time, the surface hardness of each concrete type is not significantly different. At an early age, the lowest rebound number belongs to P.P.C. concrete; however, at a later age, it reaches the rebound number almost similar to P.C.C. concrete. Furthermore, the concrete with a mixture of P.P.C. (50%):

P.C.C. (50%) shows the highest surface hardness in age concrete curing time. The results of concrete surface hardness are in line with the concrete compressive strength.

Table 5. Concrete rebound number

Curing time (days)	Rebound number			
	PPC (100%)	PCC (100%)	PPC(50%):PCC(50%)	PPC(75%):PCC(25%)
7	25.5	26.6	26.7	26
28	28	28.5	28.8	28.4
42	29.7	29.9	30.3	30

Discussion

Characteristics review of the cement

As indicated in Table 3, P.P.C. contains silica 1.3 times of P.C.C. Even the silica content in P.P.C. (24.17%) is greater than the silica content in O.P.C., as reported by (Sunarno et al., 2020), where O.P.C. consists of 20.23% SiO₂. Silica content in cement can improve concrete properties with lower production costs. However, the pozzolanic reaction takes place in slower progress; thus, the strength development occurs in later age (Barbhuiya et al., 2009).

Otherwise, P.C.C. in which has higher lime content, around 8% produces a higher composition of C₃S. C₃S is a compound that has a high rate of hydration, so it dries faster indicated by the lowest setting time, as mentioned in the sub-section of setting time and Figure 1. The concrete made from P.C.C. hardens with a high initial compressive strength. On the other hand, P.P.C. has a more dominant of C₂S. Therefore, the concrete consisted of this cement shows a lower hydration rate at the initial and can provide high compressive strength in later age (Tjokrodinuljo, 2007).

After both cement types are mixed, cement with a greater portion of P.P.C. (75%PPC and 25% P.C.C.) provides a more significant setting time. The smaller amount of P.C.C. provides a slower harden process; meanwhile, the equal amount between P.P.C. and P.C.C. reacts faster due to a higher lime content contributed from P.C.C. The chemical composition of cement influences its setting time, as shown in Figure 7. A higher silica content increases the cement setting time; conversely, a higher lime content decreases the cement setting time.

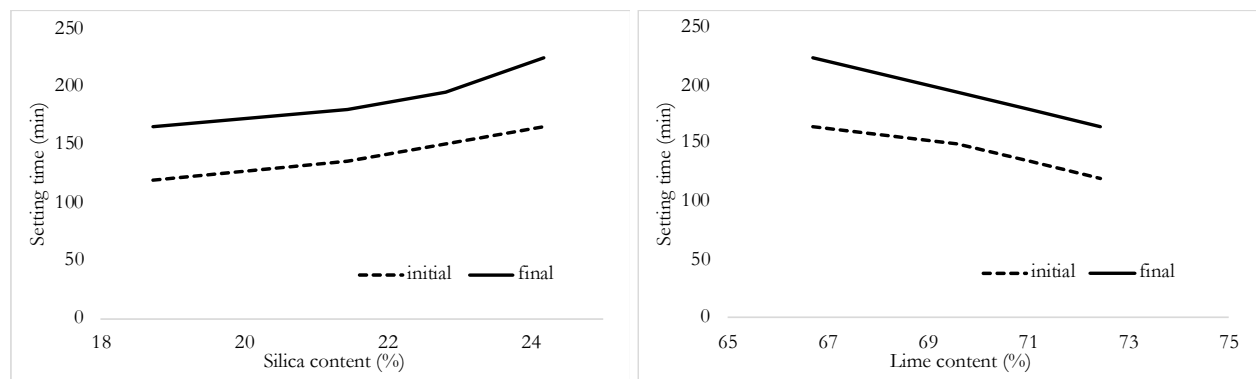


Figure 7. Influence of chemical composition on cement setting time

Characteristic review of the fresh concrete

In this paper, the properties of fresh concrete are indicated by the slump value, as shown in Table 4. The higher value of the slump leads to a concreting process to be easier. P.P.C. has the highest slump, and P.C.C. has the lowest one. Higher lime content needs more water required to be the same workable as fresh concrete with lower lime portion. A similar outcome is reported that it needs to add more than 2% water to achieve the same workability when adding 10% lime to the concrete mixture (Nawaz et al., 2016). In this study, the lime

portion in P.C.C. is 8.62% higher than that of P.P.C.; as a result, the workability of P.C.C. concrete decreases 7.65% compared to the workability of P.P.C. concrete.

The blended cement concrete types show the workability value in between the value of P.P.C. and P.C.C. concrete. A 50% P.C.C. portion in concrete mixture shows a slightly lower slump, which is 2.2% than the 25% portion P.C.C. in the concrete mixture. Furthermore, Nawaz et al. (2016) state that there is a fast reaction occurring when lime and water are contacted. The lime particles absorb the water quickly, hence the hydration process arises immediately. Due to the quick process of water absorption, it leads to need more water to be used by other compounds to be hydrated.

Characteristic review the hardened concrete

Although P.P.C. presents excellent properties on the preliminary examination (chemical composition, setting time and workability properties), the concrete with blended cement of P.P.C. and P.C.C. with a ratio of 50%:50% respectively provides the best mechanical strength and surface hardness when this binder type is used to make the concrete. This is because the influence of C_3S chemical compounds from P.C.C. and C_2S compounds from P.P.C. performs the best reaction to produce the highest compressive strength of concrete.

Considering the concrete composition of 75% P.C.C. and 25% P.P.C., despite its initial compressive strength is low, however, at 42 days testing, the compressive strength is almost equal to the highest concrete compressive strength. This blended cement type occupies the second rank of the mechanical properties and surface hardness after the concrete made of the equivalent portion between P.P.C. and P.C.C. This occurs due to the continuous pozzolanic reaction from the hydration process. The product from pozzolanic reaction improves the properties of concrete by two mechanisms, which are by providing a more binding effect between the aggregate and by producing a denser concrete by filling the concrete pores (Adesina and Olutoge, 2019).

Conclusion

P.P.C. has the characteristics of silica content, physical, and workability properties that are more prominent than either P.C.C. or mixture between P.P.C. and P.C.C. However, when used in making concrete, P.P.C. concrete has lower characteristics than the combination between P.P.C. and P.C.C.

Concrete with a mixture of 50% P.P.C. and 50% P.C.C. show an excellent compressive strength development before 28 days. However, after 28 days, the development of the compressive strength is relatively constant. Among all the concrete types, this concrete achieves the greatest average compressive strength in each curing time. On the other hand, for the concrete with blended cement of P.P.C. 75% and 25% P.P.C., despite the lower initial compressive strength but it's 42 days compressive strength is almost equal to the highest compressive strength, which produced by the concrete with a mixture of 50% P.P.C. and 50% P.C.C. Furthermore, concrete made from the blended of P.P.C. (50%) and P.C.C. (50%) also shows the most significant characteristics of Young's modulus and surface hardness.

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